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The Distributed Interactive C3I Effectiveness (DICE) Simulation

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ABSTRACT

Information Technology Division was tasked by the Headquarters Australian Defence Force to develop tools, through modelling and simulation, for effectiveness studies of Command, Control, Communication and Intelligence (C3I) systems. Such tools needed to allow for the study of systems at the strategic, operational and tactical levels, including all services and joint forces. The primary tool developed is the Distributed Interactive C3I Effectiveness (DICE) simulation in which human players are complemented by artificial agents. The DICE simulation environment can be connected to lower level battlefield simulations and war games which are used to represent the overall military mission, operation or battle. The impact of C3I aspects on the overall mission can be used to gauge C3I system effectiveness. What is termed Phase 1 of development has been completed and is reported collectively through a number of detailed documents. This report gives a substantial overview of the simulation capability along with areas of future research and development.

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DSTO Electronics and Surveillance Research Laboratory
PO Box 1500
Salisbury South Australia 5108

Telephone: (08) 259 5555
Fax: (08) 259 6567

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Executive Summary

Information Technology Division was tasked by the Headquarters Australian Defence Force to develop tools, through modelling and simulation, for effectiveness studies of Command, Control, Communication and Intelligence (C3I) systems. Such tools needed to be general-purpose to allow for the study of systems at the strategic, operational and tactical levels, including all services and joint forces. The primary tool developed is the Distributed Interactive C3I Effectiveness (DICE) simulation for which Phase 1 of development has been completed. This report gives a substantial overview of the simulation capability along with areas of future research and development. The simulation has the following key features:

- The ability to graphically define the network of nodes and links that form the central C3I system under examination.
- The ability to represent communication over network links through stochastic or deterministic time delays.
- The ability to specify a scenario under which the C3I network will be exercised.
- The ability to artificially represent and emulate over time the functionality (input, output and internal activities) of network nodes through the use of artificial agents.
- The ability (optional) to assign human players to represent the actions of network nodes. A standard language is needed for communication between human players and artificial agents; ADF and DICE-specific Australian Defence Formatted Messages (ADFORM) are used. A variety of ADFORM-related software has been developed including a graphical user interface (GUI) facility permitting human players to receive, create and submit ADFORM messages.
- The ability to define appropriate measures-of-merit (MOM) to be used in a particular study and to develop artificial agents for the computation of those

measures during run time. The ability to specify mission requirements for each measure.

- Simulation controller facilities for run-time monitoring and control.

- A simulation kernel that allows interoperation of autonomous artificial agents, human player facilities, controller facilities and PUI for interfacing to battle simulations and CSS, for example. A single and multiple execution capability exists as well as flexible execution rate.

- A core relational database architecture.

- Post-simulation analysis facilities allowing inspection of single and multiple simulation execution data. Features include the inspection of information flows and general effectiveness analysis through comparison of MOM values against mission requirements.

- An interface that allows interoperation of the DICE simulation with an in-house developed air defence simulation ADSIM. Interfacing to tactical battlefield simulations and war games permits inspection of the impact of C3I aspects on the overall military mission in order to gauge C3I system effectiveness.

- A partially-developed interface that will lead to full compliance with Distributed Interactive Simulation (DIS) protocols.

In addition to the DICE simulation, a Petri net explanation and analysis capability and GUI environment for conveying the underlying characteristics of a Petri net agent to a military domain expert was developed.

Simulation is a burgeoning technology within the Defence community. In particular, in the area of C3I, the interoperation of simulated and real systems is regarded as a key requirement for mission rehearsal and other forms of training that also facilitate subsequent analysis. A follow-on task will address the following areas:

- The provision of simulation technology to the Defence organisation;

- Further development or acquisition of tools for C3I analysis;

- Applications to Defence studies;

- Interfacing simulation with operational C3I systems; and

- General measure of effectiveness and analysis R&D.

Experiences and capabilities gained from the above ventures, along with research in the fields of artificial intelligence, DIS and performance optimisation, will significantly influence future development of the DICE simulation.

Authors

Mike Davies
Information Technology Division

Mike Davies is a senior research scientist with a BSc(Hon) in applied mathematics and a PhD in mathematical modelling. His career at the DSTO has involved the application of mathematical modelling and computer simulation to the analysis of human performance in ground-based air defence systems and aircraft navigation and weapon delivery. His current research interests concern the evaluation and enhancement of military Command, Control, Communication and Intelligence through simulation-based analysis and training.

Carsten Gabrisch
Information Technology Division

Carsten Gabrisch is a professional officer with a BSc in applied mathematics. His career at the DSTO has involved the application of mathematical modelling and computer simulation to ground-based air defence systems and the development of a deployment tool for ground-based air defence systems. Currently he is involved in the development of simulation tools to study the effectiveness of Command, Control, Communication and Intelligence.

John M. Dunn
Information Technology Division

John Dunn completed a Bachelor of Applied Science degree in Mathematics and Computing at the South Australian Institute of Technology in 1988. He has worked at DSTO for seven years and is a Professional Officer primarily involved in programming and computer support on PC and UNIX based systems.

Fred D.J. Bowden
Information Technology Division

Fred Bowden completed his Bachelor of Science at Murdoch University in 1989 majoring in Mathematics and Physics. He joined Combat Systems Division (now part of Information Technology Division) in 1990. In 1993 Fred completed a First Class Honours degree in Applied Mathematics at the University of Adelaide. He is currently studying for a doctorate relating to the application of extended Petri nets to military Command, Control, Communications and Intelligence systems.

Contents

Abbreviations

ADF	Australian Defence Force
ADFORM	Australian Defence Formatted Message(s)
ADFORMS	Australian Defence Formatted Message System
ADSIM	Air Defence Simulation
AEW&C	Airborne Early Warning and Control
AIM	ADFORMS Interface Machinery
AMS	ADFORMS Management System
C3I	Command, Control, Communication and Intelligence
CAP	Combat Air Patrol
CE	Control Element
CGF	Computer Generated Force
CSS	Command Support System
DICE	Distributed Interactive C3I Effectiveness
DIS	Distributed Interactive Simulation
DSDME	DICE Simulation Development and Management Environment
GBR	Ground-Based Radar
GUI	Graphical User Interface
ITD	Information Technology Division
MOE	Measure of effectiveness
MOM	Measure of merit
MOP	Measure of performance
NADOC	National Air Defence Operations Centre
ORBAT	Order of battle
OTHR	Over-The-Horizon Radar
PDU	Protocol Data Unit
PN	Petri net
PU	Peripheral unit
PUI	Peripheral unit interface
RAP	Recognised Air Picture
RCC	Regional Correlation Centre
ROE	Rules of engagement
SADOC	Sector Air Defence Operations Centre
SQN	Squadron
TAOC	Tactical Air Operations Centre

1. Introduction

As stressed in the Australian Defence White Paper of 1994[1], effective Command, Control, Communication and Intelligence (C3I) of Australia's forces is fundamental to the successful conduct of Australian Defence Force (ADF) operations, in any conflict or peacetime activity. Accordingly, there is a drive to identify and remedy the weaknesses of existing C3I systems and to specify and work towards goal architectures for the future. Having the ability to study the effectiveness of existing and future military C3I systems is essential to this process. Information Technology Division (ITD) was tasked to develop modelling and simulation tools to enable such studies to be conducted.

A typical C3I system structure for the defence of Australia might involve elements of the three services and accommodate conflict at all levels. The strategic level embraces the higher echelons of the military and political organisations concerned and hence addressing this level requires addressing decision-making at lower (operational and tactical) levels also. The C3I architecture can be pictured as a complex network of nodes and links. The nodes are typically centres of decision making; information processing or filtering; information transfer; or combinations of these. The links are the inter-node communication channels that transmit many forms of information. In a time of conflict, the C3I system might be stimulated by intelligence concerning the detection of potentially hostile enemy activity. This would consequently cause the generation and passage of internal information that might result in changes in readiness and maybe the deployment of reaction forces. To study the effectiveness of military C3I systems requires analysis of the impact of C3I procedures and technologies on the overall military mission concerned. The term *mission* is used here to describe, for example, an operation, battle or exercise for which there exists one or more military objectives that need to be attained.

The requirement on ITD was not to develop tools specific to any particular military service or level of conflict, but rather to create a general purpose suite of tools, specific instances of which could be used to address any particular study at hand. It was decided that the main means of achieving this suite of tools and the associated skill base would be through the process of developing an interactive simulation with some capability for remote participation. The goal tool is known as the Distributed Interactive C3I Effectiveness (DICE) simulation.

Research and development of the DICE simulation and associated tools was initially conducted under the DGFD(Joint)-sponsored C3I Simulation Studies task ADF 93/237. At the completion of this task, the simulation was developed to a significant stage, referred to as Phase 1, upon which future developments

will build. This document reports the general aims and features of this Phase 1 capability along with areas of future research and development.

2. General Requirements and Features of the DICE Simulation

2.1 Interactive capability

It was identified that the nucleus of any software tools developed under this task should be an interactive simulation with some distributive capability that enables participation by a number of possibly remotely located human players. The interactive nature must allow the decision-making practices of real commanders to be injected and accommodated in a adequately realistic manner. For this reason, access to real-world or trial command support systems (CSS) by the human players is a desirable option.

2.2 Artificial agents

The human players need to be complemented by a number of artificial ones (artificial agents) in a manner whereby the two types can communicate. The artificial agents need to be modular in construction and adequately realistic representations of the real-world entities that they emulate. Artificial agents might represent individual, or groups of, commanders in a C3I system or an aggregated representation of some C3I sub-system or entity. The underlying assumptions and characteristics of these agents need to be clearly conveyable to a military domain expert.

2.3 Application development environment

An application development capability that includes scenario generation is required that can be easily employed by analyst-assisted military personnel. A typical application can be regarded as centred about a complex set of nodes and links that represents the central C3I network under study. The real and artificial players would generally form the nodes of this central network that is exercised by some specified scenario. The central network is surrounded by an external environment that encompasses any aspects that are not explicitly represented in the central network but which, nevertheless, form important contributions to the scenario being addressed. What lies outside the central network and what lies within depends on the depth and breadth of the scenario being simulated. The external environment embraces such aspects as enemy activity, battlefield information, and sensor information which might be represented by individual models, simulations or simple look-up tables. The external environment can be

considered to inject stimuli into the central network and be influenced by the actions that eventuate from that network.

2.4 Communications

In real C3I systems, communications between nodes can take many forms including formatted and unformatted messages; tables of data; graphical displays; and video images. In the DICE simulation, a standard form of communication is required to reduce information ambiguity and facilitate information exchange between both human and artificial players. Communication between the central network and the external environment also needs to be achieved through the use of this standard. A language based on formatted textual messages is required; such messages can either bear a direct resemblance to a military message, or accompany or summarise information of a different form. Having a standard language, understandable to both humans and machines, for information exchange is also a major requirement in command and control systems of the ADF. The Australian Defence FORmatted Message System (ADFORMS)[2] is the agreed standard for the ADF and this standard has been chosen as a foundation in the DICE project[15].

2.5 Tactical environment

Interfaces to tactical level models and simulations that represent the external environment are essential. This capability permits the impact of the represented C3I system on the military mission concerned to be determined and hence allow evaluation of the system's effectiveness. Such models and simulations may be themselves remotely located and hence the ability to interoperate in a distributed environment is again important.

2.6 Modes of execution

For flexibility, the simulation needs to be capable of running in interactive and non-interactive modes and have variable execution rate allowing real-time and non real-time execution. A multiple execution capability for parameter sensitivity study and Monte Carlo type analysis is another important requirement.

2.7 Analysis capabilities

An extensive analysis capability is required to allow effectiveness evaluation to be conducted; this might include a replay facility and history and review capability.

References 13 and 14 report a method of comparing C3I system measures of performance (MOP) with mission requirements in order to determine the

effectiveness of a C3I system. The method is based on the premise that the effectiveness of a C3I system is to what extent that system satisfies the mission requirements of that system. The philosophy of the DICE simulation project is that the effectiveness of C3I would be evaluated by inspecting its impact on the overall military mission being addressed. The work of references 13 and 14 accommodates the question "how much impact is good enough?". The terms performance and effectiveness will be adopted temporarily.

The following stages can be considered in determining the effectiveness of C3I systems, namely (the word 'system' is used quite loosely here):

(i) Decide what is and what is not the C3I system to be examined; determine the boundaries of the system;

(ii) Determine suitable MOP for the C3I system which are independent of, and hence will not be influenced by, events outside the boundaries of that system (multiple MOP may be required);

(iii) Determine mission requirements in terms of the system MOP;

(iv) Compare system performance against mission requirements to determine overall effectiveness.

In references 13 and 14, system MOP and mission requirements are expressed as continuous functions of independent parameters that are modelled or analysed independently but in a common context. Given these functions, the extent to which the mission requirements are met is determined through n-dimensional geometric integration applied to the system MOP and the mission requirements locus. The authors state that simulation may be one means of determining the continuous functions concerned. However, if the study matter is complex then such functions may be actually statistical in nature and hence difficult to represent in an analytical or continuous manner. One means of addressing such a case is to evaluate the overall effectiveness by comparable statistical means; this would require knowledge of the exact statistical nature of the system. Another method of addressing this problem is through multiple executions (eg for Monte Carlo purposes) of a simulation of the system under examination.

This approach was considered useful, to adopt it required establishing particular but more general-purpose capabilities. Stages (i) to (iii) above can be problematical steps in system analysis and the DICE simulation would not be expected to solve such problems although its application may result in a better understanding of the problem domain. A general facility for specification of system measures and mission requirements (optional) against those measures

was required. The simulation itself would be associated with the actual implementation of Stage (iv).

The overall characteristics of the DICE simulation are summarised in Figure 1 which is essentially a breakdown of the functional areas of the DICE simulation environment. Indicated by the uppermost row of this figure are the *players* in the simulation, namely the simulation controller or analyst; artificial agents; and human players. *Peripheral units* (PU) in the DICE environment include any war games and battle simulations etc. that may be employed to represent tactical aspects, plus CSS that may be required by the human players. Players plus PU are considered the nodes in the overall DICE simulation, ie the central network plus the external environment. The simulation *kernel* is the central engine of the simulation itself and can be used to emulate the communication delays between the nodes. A relational *database* plus associated management utilities are employed extensively by the simulation in order to facilitate distribution of the simulation processes; communication between nodes; the sharing of common information; and the overall analysis capability.

The overall development of the DICE simulation and associated tools and facilities are integrated under the DICE Simulation Development and Management Environment (DSDME). As illustrated in Figure 2, this environment has two main streams; the Management stream and the Simulation & Analysis stream. The Management stream is associated with the provision and maintenance of general library facilities for use by specific instances of the DICE simulation. The Simulation & Analysis stream is application specific and is concerned with the specification of the C3I system to be studied and the development, simulation and analysis of particular scenarios that exercise it. This report will be delivered by conveying the requirements, current status and future research and development for the DICE simulation project in the context of the DSDME areas. A detailed technical description of the simulation, including a worked example application and underlying mechanics, is given in reference 16. An overview of a similar example is given in Section 5 of this report along with the perceived future research and development activities summarised in Section 6.

Software has been implemented primarily using the ANSI 'C' programming language on Sun SPARCstations with Graphical User Interfaces (GUI) developed under XWindows and Windows 4GL.

3. DICE Simulation Management Capabilities

A goal of the DICE simulation project is to establish and maintain libraries of artificial agents and their building blocks; peripheral units and their interfaces;

and standard messages. These libraries will then be available for general use by specific instances of the DICE simulation. This goal is particularly demanding in that the libraries must be general-purpose in nature and be able to be used in a variety of applications. Realistically, individual applications of the DICE simulation can be expected to result in extensions and modifications to the libraries but the aim is to achieve general-purpose facilities.

The GUI framework for the DSDME has been developed and forms an umbrella under which all software and future development is integrated. The current version of this environment[16] embraces all of the capabilities reported in this document; the DSDME will continue to be modified as further developments are made. There are two streams within the management area of the DSDME; namely, *agent management* and *message management* which are addressed in the following sections.

3.1 Agent management

The agent management stream provides facilities for the general management of Petri net artificial agents; peripheral units and their interfaces; human player facilities; measures-of-merit (MOM); and additional artificial agents (non-Petri net).

3.1.1 Petri net agent management

Extended Petri net (PN) simulations form the primary artificial agent capability within the DICE simulation to date. This section will be used to describe some general requirements for artificial agents as well as summarising the use of PN (details of PN have been reported separately in references 6 to 8).

The artificial agent management stream needs to provide:

- facilities for artificial agent development;
- facilities for artificial agent explanation and analysis; and
- a library of existing artificial agent building blocks.

The initial requirement of artificial agents in the DICE simulation was that they be essentially rule-based but yet still exhibit some important properties; namely that a *role-based* methodology can be employed in their design and implementation; that they can represent concurrent and sequential processes and resource sharing; and be clearly conveyed to a military domain expert.

The role-based methodology[8] involves a natural breakdown of the artificial agent processes into smaller components, loosely referred to as *roles*. A role is

not necessarily the base element of the agent, as in the work of reference 3, it is more a function, which may in turn have many roles within it. This structure leads to a hierarchical design technique, meaning that the artificial agent roles can be designed initially and then brought together to form the overall artificial agent, leading to a bottom up design approach. Alternatively, the designer can initially sketch out the basic functions of the artificial agent and then add detail by enhancing its roles independently, leading to a top down modelling approach. The artificial agent being modelled and the information about the agent will determine which method is most appropriate for the task at hand. The resulting structure facilitates modification of agents.

The library facilities with regard to artificial agents, then, are to make available basic building blocks, namely roles, that can be brought together to form agents for specific application. This is particularly important since what constitutes a role within an artificial agent of one application may be an artificial agent in itself in another application.

C3I networks involve many different systems or entities working both concurrently and sequentially towards the same main objective. This is also true for each of the nodes in the system. This is an important feature of any decision making process and so must be reflected in the artificial agent design such that the agent can represent activities which occur in series and in parallel. To some extent this is dealt with by taking the role-based approach, where roles can be arranged according to the way their related functions occur in the real system.

Adequate credibility and realism in artificial agents is essential; judgement of such qualities can generally be best made by military domain experts. The underlying assumptions and characteristics of artificial agents need to be conveyable in a form easily understood by a military expert. Such an expert should be able to interrogate features of the agents, have that agent explain its actions, and to form some judgement on the realism of that artificial agent compared with the real-world system that the artificial agent represents. Having military endorsement of the assumptions used in such representations is a vital prerequisite to any C3I system study. Such an explanation and analysis capability is recognised as being important by other researchers and developers of computer generated forces (CGF) in the Distributed Interactive Simulation (DIS) field[4, 5].

Petri nets (PN) where originally developed by Carl Petri as a means of modelling computer systems. Since their original conception they have been used to model and analyse many different types of systems including C3I systems and decision makers[3]. PN are ideal for the modelling of event systems which involve the problems of resource sharing, concurrent and sequential processes, and synchronisation. The main problem with PN is the

growth in model size as the systems they represent become complex. To overcome this problem PN have been extended by the introduction of features such as coloured tokens, firing modes and hierarchies. These extensions allow the user to represent more complex systems in a manageable way; however, they do not increase the modelling power of PN.

The modular graphical representation of PN and the hierarchical extension allow the role-based methodology to be easily applied during design[7, 8]. Each role can be thought of as a PN which is then joined to other PN via common places and transitions (the *nodes* of a PN), this allows each of the roles to be designed individually and then brought together. Alternatively a PN can be constructed that outlines the artificial agent structure which can then be refined by adding detail. Hence a top-down or bottom-up approach is possible. The commercial software package *AlphaSIM*[18] is used to design and develop the roles for PN agents; other packages are also being investigated.

PN were chosen over other techniques for a number of reasons including the associated ease of modification; the underlying mathematical foundation; and its inherent ability to represent synchronisation, concurrency and resource sharing[8].

Each PN agent is implemented as an event-stepping simulation[6]. Within the PN simulation itself, communication is achieved through the passage of tokens distributed through the firings of transitions. When an agent communicates with the remainder of the simulation, however, it must be done through the standard ADFORM format. Hence a two-way translation is required between the ADFORM and the PN languages. A user interface facility[15] has been developed for the specification of mapping information describing how ADFORM need to be decomposed into input token attributes and how output attributes are to be used to build ADFORM.

A PN explanation and analysis capability has been established using the declarative language Prolog[7, 8,11]. The analysis component interrogates a given PN according to user-specified goals or queries whilst the explanation capability abstracts and translates the query results such that they are presented in a form more easily understood to someone less versed in PN notation. The explanation capability is achieved through the use of declarative tags on the PN that describe the significance of particular actions and state components. Reference 7 is a detailed report on this capability with reference 11 reporting the source code for the software. A graphical user interface (GUI) environment has been developed for this capability.

3.1.2 Peripheral unit (PU) management

The PU management stream provides:

- Facilities for peripheral unit interface (PUI) development;
- Facilities for specifying PU information; and
- A library of existing PUI and associated information.

Tactical-level (eg battlefield) simulations, and maybe wargames, would be used to represent activities that are external, or at a lower level, to the main C3I simulation and help portray the overall military mission concerned. Such representations allow the impact of C3I to be gauged and hence associated effectiveness measures determined. In addition, CSS may be needed for employment by human players. Interfacing of such peripheral units to the main DICE simulation is achieved through Peripheral Unit Interfaces (PUI).

Library facilities with regard to PU, then, are to provide access to PUI that can be employed as required for specific application. It is important to note that the intention is to only have one PUI for a given PU, ie a PUI is not scenario-specific but may get extended to cover the requirements of new scenarios.

Investigations have been made into the feasibility of interfacing selected tactical-level simulations and CSS, for scenarios of immediate interest, with the DICE simulation. A two-way interface to an in-house developed air picture simulation (ADSIM)[12,19] has been achieved and used to demonstrate many of the concepts of the DICE project including MOE evaluation and the use of command support tools by interactive human players.

Significant breakthroughs have been made by the US in the interoperation of autonomous distributed interactive simulations. The evolving standard is that of Distributed Interactive Simulation (DIS)[9,20]. The general PUI development discussed in previous paragraphs only holds for PU that are not DIS compliant. Efforts have been made to make the DICE simulation compliant with DIS standards to enable interfacing with PU that are possibly geographically distributed. Such PU would be themselves DIS compliant and hence have an existing interface capability. These efforts are centred on developing what can be regarded as a DIS PUI - an interface into the world of a DIS exercise. Communication in a DIS exercise is achieved through the use of standard messages referred to as Protocol Data Units (PDU). The DICE simulation's DIS PUI is currently able to receive and send the main DIS PDU and this capability has been demonstrated. It is important to note that being DIS-compliant helps but does not ensure interoperability. A significant effort is still required to form a consistent simulation exercise with the credibility and fidelity needed for analysis or training.

(i) Peripheral unit interface (PUI) development

In general, PU such as battle simulations are employed in a given application to help achieve the necessary depth and breadth to a scenario being represented. PU are therefore expected to provide some service to the remainder of the simulation and requests for such services are in the form of ADFORM. Interfaces with PU are required then to translate such requests into appropriate input directives for the PU concerned. Similarly, a reverse translation is required from the outcomes of the PU into ADFORM. Matters that need addressing by such interfacing include therefore the blending of spatial and temporal based tactical models with the message or information flow based C3I simulation. Although some CSS may be regarded as stand-alone or off-line, the interfacing problems that apply to battlefield simulations can be considered to apply here also except that the problems extend beyond the passage of messages. CSS are generally driven by *real-world* data which, in the DICE environment, is simulated. The CSS will be providing information to support the commander that utilises it.

This environment provides facilities to develop and compile the 'C' computer code for a PUI. A skeletal yet compilable framework is provided that, upon execution, establishes the message input/output mechanisms and carries out all the required database transactions.

(ii) Peripheral unit information

There are two information files associated with a PUI:

(a) Stimuli Format; and

(b) Output Category.

The Stimuli Format file specifies what format the input directives for the PU need to take and how such directives should be passed to the PU itself. Ignoring DIS-compliant PU, input directives might be passed to a common file or files that are monitored by the PU allowing sensitivity to such stimuli. Reference 19 gives an example of this type of configuration.

The Output Category file includes the concept of *tassels* which relates to the PUI having a number of arms emanating from it, the loose ends of which need to be tied down when that PUI (and hence the associated PU itself) is employed in building a scenario. The tassels signify the different categories of information that a peripheral unit can supply to other nodes in the simulation. Tying of the tassels specifies what entities in the simulation require what information from the peripheral unit and is covered in Section 4.1.3.

If a new PU is being established then skeletal versions for these files are available and presentable to the user for further development. The concept of tassels also holds for the artificial agents.

3.1.3 Human player facility management

A number of human player facilities have been developed that permit the receipt, creation and submission of ADFORM messages[15]. A suite of facilities can be expected to arise as application of the DICE simulation increases and exposure and interfacing with real CSS occurs. The human player facility management stream will provide a means of managing the availability of these facilities and their use within particular applications.

3.1.4 Measure-of-merit (MOM) management

As discussed later, in order to inspect particular measures of performance, effectiveness etc., there is a need to design and implement an associated artificial agent that will compute such quantitative measures. Whilst it can be expected that measures will be specific to particular applications or studies, this management stream will provide a general area for managing these agents.

3.1.5 Additional artificial agent management

In addition to PN, other relatively simple techniques that can be easily adopted for artificial agents include look-up table and simple algorithm-based approaches. This management stream provides a facility for collation and administration of these agents. Capabilities that may eventuate from exploring the area of artificial intelligence[17] may be incorporated within this stream or may warrant a separate facility similar to that for PN.

3.2 Message management

As mentioned earlier, the standard communication language in the DICE simulation is one based on ADFORM. The message management stream provides:

(i) Facilities for inspecting ADFORM that originate from the ADF;

(ii) Facilities for specifying, modifying and inspecting DICE-specific ADFORM; and

(iii) Facilities for specifying the logic by which artificial agents and PU will interrogate and build ADFORM. Such logic forms a mapping between the ADFORM language and the internal database of the agent or PU.

Reference 15 gives a detailed account of the ADFORM facilities within the DICE simulation. Library facilities are to provide standard message structures that can be employed as required for specific applications. The message

structures are not scenario-specific but it can be expected that the DICE-specific messages will get extended to cover the requirements of new scenarios as they are addressed. The ability to specify, modify and inspect DICE-specific ADFORM is important since there is a need to emulate many forms of communication (including telephone, fax etc) for which ADF ADFORM might not exist.

4. Simulation & Analysis

The Simulation & Analysis stream makes use of the standard library facilities associated with the management stream, to build, execute and analyse a DICE simulation application.

4.1 Application Development

A typical application of the DICE simulation is configured about a central network of nodes and links under study. Human and artificial players need to be assigned to these nodes to represent their behaviour. The characteristics of network links also need to be specified and represented as well as the environment within which the C3I network lies. Peripheral units and additional artificial agents might form nodes within this external environment and represent friendly and hostile forces, sensors and other systems as required.

The C3I network is exercised by a generated scenario which translates into stimuli for the network. Description of suitable measures-of-merit (MOM) which reflect the overall analysis focus of the simulation exercise is also needed. (MOM is a generic term used to encapsulate such terminology as measures-of-performance (MOP), measures-of-effectiveness (MOE) and measures-of-force-effectiveness etc. This has been chosen to purposefully emphasise the general purpose nature of the DICE simulation.)

A variety of facilities have been developed to support network definition and scenario generation and these are covered in the following sections.

4.1.1 Network definition

One feature of the application development suite of tools is a general-purpose drawing environment (*ScenGenDraw*) which enables the definition of a network of nodes and links. This tool is used in this stream to define the C3I network that is central to the application. Both nodes and links can be represented by tailored symbols and have associated general information that includes unique identifiers and descriptions. Multiple links can be present between nodes to represent, for example, different communication channels or media.

The characteristics of a communication channel is currently limited to a deterministic or stochastic transmission time. For flexibility, in a two-way communications link the transmission time (or the parameters that affect it) can be different for each direction. A more sophisticated communications model may be acquired or developed in the future that takes explicit account of link bandwidth and the actual traffic on a link at any instant during the simulation.

The link characteristics are specified by the user within the ScenGenDraw environment and stored with each visual link. This information is directly used by the simulation as discussed later. ScenGenDraw also allows free-text storage of general notes against each node and link which is useful for general system specification and application development.

In terms of the eventual simulation, the overall output from this environment is the network nodes and links, their description and their connectivity. Connectivity is described using link names, source and target node names and the transmission time information for each link direction.

The Simulation Controller node is automatically generated which corresponds to the run-time monitoring and control facilities associated with the simulation controller. Each node has the ability to communicate with the Controller node and the necessary links are automatically generated.

The C3I network that results from the ScenGenDraw facility has the potential to be used for run-time display.

4.1.2 Overall scenario definition

This stream concerns the specification of how the central C3I network will be exercised. The current capabilities are adequate but can be considerably enhanced leading to a more sophisticated graphics-based environment and improvements in overall robustness. This would include map displays and the ability to specify from those displays information pertaining to own and enemy forces, their initial status, rules of engagement (ROE) and intentions or plans.

However sophisticated the desired scenario generation capability, the resultant output has to be translated into stimuli that will prepare every node agent, peripheral unit and human player facility for simulation execution and stimulate such nodes during run time. In the DICE simulation architecture, the conveyance of such stimuli is achieved through ADFORM. With the absence of sophisticated user facilities, the scenario generation capability currently consists of the ability to directly specify the stimuli as ADFORM messages.

This facility addresses specification of the initial state of the scenario and the scheduling of pre-determined stimuli. Such stimuli are referred to as *independent* since they are pre-scheduled to occur at certain times in the simulation, and

hence are independent of activities that occur whilst the simulation is running. Independent stimuli can be received, and considered sent, by any node in the simulation; early stimuli form the initial drive to the simulation. Initial independent stimuli might specify the initial position, state and perceived intent of enemy entities; the initial ROE; and the initial military objectives of the blue force. Independent stimuli scheduled to occur during run-time might represent aspects such as pre-determined additional enemy activity.

Specification of the ADFORM-based independent stimuli involves selecting the format and building message content; selecting intended recipients; and scheduling message submission[15]. When specifying the recipients of independent stimuli, the option is available for either direct transmission to the recipient or transmission via the communications module of the simulation kernel. In order to minimise the processing that occurs at the commencement of execution, some independent stimuli can be flagged as initialisation messages which are subsequently handled before simulation time t = 0.

4.1.3 Peripheral unit allocation

This stream allows peripheral units (PU) to be selected from the standard library and configured via their PUI into the scenario concerned. PU will be selected based on what service is required of them in the scenario.

As discussed earlier, each PUI (and hence the associated PU) can be considered having a number of *tassels* emanating from it which correspond to particular types of categories of information that that PU can provide to other nodes in the simulation. The information takes the form of ADFORM. These tassels need to be tied down to particular recipients with the default being to link tassels to nobody. Multiple recipients of information are allowed and PUI can broadcast all information to all nodes if required. This broadcast characteristic typifies current DIS exercises[9,20]. The specific link on which the messages are to be submitted must also be stated. Also, the option of transmitting or not transmitting the messages via the kernel communications module is again available.

4.1.4 Measure-of-merit (MOM) allocation

The MOM definition facility can be regarded as allowing use of an artificial agent that calculates the MOM that are considered to apply in a given scenario. A number of MOM might be appropriate and this facility also includes the ability to specify mission requirements for each MOM. Mission requirements currently take the form of lower and upper bounds on each MOM. The resultant MOM values can be compared during run-time and in post-simulation analysis against mission requirements to determine the extent to which the requirements have been met. In the case of a MOM which is regarded as a MOP, observing the

MOP of a system and comparing observations against requirements is one means of judging the overall effectiveness of that system.

Although the general philosophy for effectiveness analysis in the DICE simulation is based on inspecting the impact of C3I on an overall military objective, it is important to note that any quantitative MOM can be calculated and used in a study. An artificial agent (a MOM agent) would be designed to compute the required measure and be configured to receive input information from other nodes as needed[16].

The concept of tassels applies to MOM agents also in that the service they provide are the MOM calculations which need to be assigned to appropriate recipients. The recipient of MOM calculations is generally the Controller node which might consequently display the calculations to the analyst.

4.1.5 Petri net allocation

This stream allows Petri net artificial agents to be selected from the standard library and configured as players in the DICE simulation. Players represent the nodes of the central C3I network and a number of artificial players may be required with their detail being dependent on what service is required of them in the scenario. Such agents are formed through adoption of the role-based methodology discussed in Section 3.1.1. The concept of tassels applies to artificial players also.

For completeness, it is mandatory that artificial players are allocated to each node in the central C3I network regardless of intended human player allocation. This is important and allows multiple executions of the simulation to be achieved without the presence of the original human players.

4.1.6 Human player allocation

The main function associated with the human players in the simulation, is the ability to receive, create and submit messages such that communication with the remainder of the simulation is achieved. GUI environments have been established that provide such a capability[15]. An overall goal is to utilise original or tailored versions of operational software that provide this capability to real-world military personnel. The ADFORM Interface Machinery (AIM) software, developed for the ADF, is an example of operational software that will be configured as an optional feature within the DICE simulation architecture; its longer-term adoption will be dependent on the associated throughput and ease of integration and use. Interfacing to real-world CSS has not been attempted to date, although the basic concepts have been demonstrated using the ADSIM model.

This stream allows specification of what software will be used to form the stations for human players in the DICE simulation. Although possibly standard

across scenarios, such allocation includes the facilities that will be used by the simulation controller.

When applying the DICE simulation, clear intentions are essential concerning what key areas or capabilities of the represented C3I system were to be addressed. The presence of human players in a simulation exercise increases the likelihood of the simulation taking a course that is not on path to meeting the overall objectives of the exercise. The controller needs to be able to recognise such situations and influence the simulation during run-time in order to nudge it back on course. The controller needs, therefore, to be able to communicate with all players (real or artificial) and to inject stimuli during run-time into the simulation. The controller can secretly pretend to be any one player and send messages to others if he wishes to influence the simulation execution in that way. The controller can pause, advance and resume the simulation as needed. The controller facilities are extended versions of the human player facilities and allow the controller to cover any minor incompleteness in the scenario that has occurred through error in scenario generation[15].

4.1.7 Additional artificial agent allocation

Additional artificial agents are required to further populate the simulated scenario and represent entities or activities that are considered external to the central C3I network and have not been covered by peripheral units. Their allocation is identical to that of artificial players discussed in Section 4.1.5. Examples of such agents are enemy force behaviour and look-up tables of sensor capabilities.

4.1.8 Pre-implementation analysis

Some analysis capability is desirable at the scenario generation stage to check, for example, the completeness and fidelity of the specified scenario and make some predictions of the sequence of events that might occur. Currently simple connectivity checks are made on the C3I network but additional desired capabilities, not yet implemented, include:

- Preliminary execution of artificial agents;
- Simulation performance predictions including inspection of what data staleness or latency might occur and whether it can be adequately compensated for;
- Consideration of the distributed nature of the simulation and whether the multiple processes have been sufficiently distributed between available processors.

Currently, the only substantial pre-implementation analysis capability is provided by access to the PN explanation and analysis capability.

4.2 Simulation implementation and execution

4.2.1 Simulation implementation

The application development stage results in a collection of interrelated flat files that contain a full description of the C3I network and the external environment and scenario that drive it. In preparation for actual execution, the data needs to be implemented in a form understandable to the run-time mechanisms of the simulation. This involves converting the flat file representations into appropriate tables within an Ingres[10] relational database. A GUI environment has been developed that provides this capability for a user-selected application.

The database design of the DICE simulation is detailed in reference 16; the specific application information is converted into rows of data in the following tables. The environment allows viewing of each of the resultant tables.

Node Table: this table stores a description of the node; the processor that the associated process will execute on; and the type of node (eg Petri net, MOM etc.)

Link Table: this table stores the type of link (eg radio, fax etc.); the source and target nodes that that link connects; transmission time information; and the current link availability. Links can be available, not available and notifiable (in which case the link is unavailable but any node that wishes to use that link gets informed of its state).

Independent Stimuli Table: this table stores independent stimuli, their scheduled time and indications of which are for initialisation purposes.

Scenario Information Table: this table stores the simulation execution rate, multiple execution requirements and latency recording option setting.

Scenario information not placed into tables at this stage concerns tassels and their allocated recipients. This information is addressed in the initialisation phase of simulation execution.

Also included in this facility is the ability to specify requirements for multiple executions of the simulation. This takes two forms. The first allows specification of parameter variations (in the form of initial and final value and increment) that need to be observed from run to run. The second is the specification of the number of runs required for Monte Carlo style execution in order to observe the statistical nature of an application. For each set of parameter values, the number

of Monte Carlo executions are carried out. Parameters might describe the behaviour of nodes, links or peripheral units provided these entities are 'data-driven' to allow their behaviour to be altered between executions.

The central DICE simulation is typified by multiple processes corresponding to individual artificial agents, PUI etc. Each process can execute on any processor that has access to the core Ingres RDBMS. Part of the simulation implementation facility involves specification of how each process should be distributed[16].

4.2.2 Simulation execution

Simulation execution is in two distinct phases; an initialisation phase and a run-time phase[16].

(i) Initialisation phase

The initialisation phase prepares all scenario node processes for simulation. This phase involves:

- Establishing node processes on specified processors;
- Establishment of mailboxes and, where appropriate, tassel tables for all nodes;

  The mailboxes are database tables that store and allow retrieval of incoming message identities. The tassel tables describe the tassel allocation for a given node.

- Registration for database events;

  Database events are triggered when certain actions (eg an entry) are made on database tables. Such events are used to indicate, for example, message arrival to recipients[16].

- Conveyance of initialisation information (appropriately flagged independent stimuli) to each process and the accommodation of that information by the recipient process;
- Conveyance of readiness by node processes to simulation controller.

Having an initialisation phase separate from the run-time phase is particularly important since it prevents initialisation activities from having an affect on run-time analysis. For example, accommodation of initialisation information by a PUI may take some time since such information may be substantial and essentially dictates to the associated PU what its initial state should be.

In contrast to the run-time phase, during initialisation the processes are free to execute as fast as possible since there is no inter-process communication required. When all processes have conveyed their readiness, the simulation is essentially put in a pause mode prior to the simulation controller placing the simulation into the run-time phase.

(ii) Run-time phase

The execution of the simulation during run-time is characterised by the submission of messages by nodes for transmission and the receipt of messages by nodes. The communication architecture associated with the simulation is illustrated in Figure 3 where each node is treated in an identical manner. Each node has an associated mailbox through which it receives incoming messages. Outgoing messages from a node can either be sent directly to recipients (not shown in Figure 3) or, if a communication channel needs to be utilised, can be sent via the communications module of the simulation kernel. The communications module is designed around two main events: *message submission* and *message reception*. Message submissions get translated into receptions scheduled to occur after an appropriate communication delay or transmission time.

The kernel also controls time synchronisation and execution rate of the distributed processes and can be configured such that the simulation can run in real or non-real time. The simulation is capable of being paused, advanced and resumed as required by the simulation controller. The simulation controller can also influence the simulation by injecting messages as external or other stimuli; altering the availability and nature of communication links.

The simulation is typically initiated by pre-scheduled stimuli and ends at a pre-set instant or following a decision by the simulation controller. The information flow between nodes is captured by logging every message in the Ingres database. This involves storing the message content along with the time it was sent and received, the sender and recipient. Such logging will automatically cover any messages associated with MOM computations. The internal behaviour of Petri net artificial agents can also be recorded for later inspection. Peripheral units would generally be left to their own devices regarding the logging of internal behaviour; for example, the ADSIM PU makes its own record that can be used for simulation replay.

Against each message transaction can be recorded data latency figures which indicate to what extent the processing of messages has been delayed owing to the performance of the simulation and the network it utilises. For example, a message may be scheduled for reception by a node at a simulation time of 230 s but may not actually be picked up by that node until 232 s. Such latency needs to be taken into account in any quantitative analysis that is carried out following

the simulation. Consideration of the latency figures also provides a means of determining the optimal distributive arrangement for the simulation's multiple processes. When monitoring such latency it is important to be aware of the effect on performance of the 'probe' itself; this is a difficult problem. For this reason, the latency trapping is configured as an optional capability.

The controller facilities also include the optional ability to view the current and historical latency figures and their variation over time. Another option is the ability to monitor the message rates associated with each node and link.

At the end of an execution the resultant database tables are translated into flat file format for subsequent analysis. This is also true for each individual execution in a multiple execution batch. Against each execution is stored details of the parameter values used in that run; in the case of single executions, a baseline value is assumed.

4.4 Post-simulation analysis

Post-simulation analysis capabilities need to include inspection of C3I system characteristics such as bottlenecks; command and information flow; and effectiveness measures. A history and review function is also needed that provides the ability to select and replay aspects of the simulation, including analysis of the impact of key commands or decisions made by artificial or human players. Configuration of the simulation kernel about an Ingres database will facilitate establishment of this analysis capability but has not been developed to date.

The post-simulation analysis capabilities developed to date include the ability to inspect all information associated with an individual execution, including individual executions belonging to a batch. This is achieved by re-mapping the flat file output into database tables to facilitate querying. Inspection of the message transactions that occurred in an execution is a superficial means of determining points of congestion; more rigorous techniques are planned as future development. The activity associated with a particular node or link can be determined through appropriate queries, and the internal activity of any node can be inspected through interrogation of the associated log of events. If such information were trapped during the execution, a review of the simulation performance is possible through analysis of the data latency figures.

In the case of multiple executions, summary information from each individual execution in the batch is interrogated and a means of analysing this information in terms of pre-specified MOM is provided as discussed later in this section.

The essence of the C3I system effectiveness analysis for which the DICE simulation is designed is based on the philosophy of inspecting the impact of C3I on some overall military mission. Appropriate MOM would need to be determined to reflect this and might be scenario-specific rather than generic. The DICE simulation environment allows any quantitative measure to be calculated and in this regard is therefore general-purpose. As discussed earlier, against each measure can be specified mission requirements which are currently limited to lower and upper bounds for each MOM. A number of MOM may be employed in any application in which case the mission requirements describe a region in space within which the MOM values must lie in order for the requirements to be met. This is illustrated later in this section.

The post-simulation analysis capability allows the MOM values (observations of the system) eventuating from simulation executions to be compared against requirements.

Some measures may vary with simulation time leading to some final value which is deemed to be indicative of the system under study. Owing to the availability of all message information, the post-simulation analysis facilities for individual executions permit interrogation of the variation in MOM observations over time and inspection of how this variation compares with the bounds described by the mission requirements. All or some of the measures can be used for the comparison.

Multiple executions of the simulation produce a collection of observations of system MOM under parameter variation and statistical sampling. Confidence levels for the samples need to be determined and further executions made as required.

Let the system MOM be denoted by MOM_i where $i = 1$ to n, where n is the number of MOM used to describe the system. Let the mission requirements be denoted by $MR = f_j\ (MOM_1, MOM_2, \ldots\ldots\ldots, MOM_n)$ where $j = 1$ to m, where m is the number of functions needed to describe the mission requirements. The collection of functions that make up the mission requirements can be regarded as describing a region in n dimensional space.

Each execution of the simulation will generate individual values or observations for each MOM and hence describe a point in this space. Multiple executions will result in a distribution of points; some lying within the region, others outside. In the work of references 13 and 14, the percentage that lie within mission MOP requirements region is taken to be the overall system effectiveness.

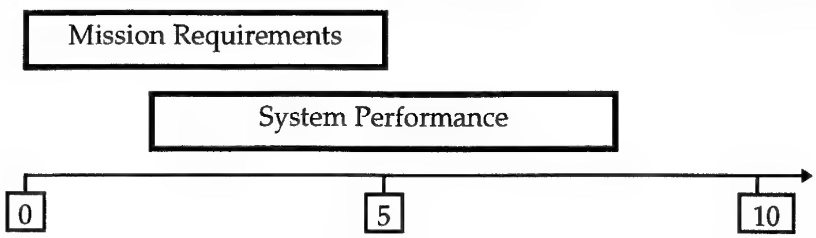
As a simple example, consider the 1-dimensional case where system performance is characterised by:

$$MOP_1 = \text{Reaction Time}$$

and the mission requirements $f_1(MOP_1)$ are expressed as:

$$MOP_1 \leq 5 \text{ minutes.}$$

The outcome of multiple executions of the simulation might be a distribution from $MOP_1 = 2$ to 8 minutes (ie a range of 6 minutes), shown in the figure below.



Assuming a uniform distribution for MOP_1, this would imply that the system is 50% effective. However, if system performance was characterised by some skewed distribution then the overall effectiveness would be less than or greater than 50% depending on where the bias lay. Multiple executions of the simulation would identify such a distribution and reflect this in the associated results.

The above example can be extended into multiple dimensions and also where the mission requirements were functions of more than one MOM (eg $MOM_1^2 + MOM_2^2 \geq 0$).

In the DICE post-simulation analysis environment, a collection of final values corresponding to each MOM is used to analyse multiple executions in batches. The percentage of 'hits' within the mission requirements region is compared with the total population. As in the case of individual executions, the selection of which measures to use in the analysis is possible.

A record of the complete analysis session, consisting of queries and their outcomes, is recorded for future reference.

5. Example Application

In order to consolidate the previous sections of this document, an example application will be conveyed. A similar example is employed within reference 16 which gives a detailed account of the mechanics of the simulation. This section will be superficial in comparison but is intended to convey a typical use of the various components that make up a DICE simulation application. The example is for illustrative purposes only and is not intended to be indicative of any real system.

5.1 Overall system

The C3I system to be studied in any application would typically be part of some broader system. Consider the example of an air defence system consisting of sensing, collation of information and response as shown in Figure 4. The sensors are Over-The-Horizon-Radar (OTHR), Ground-Based Radar (GBR) and Airborne Early Warning and Control (AEW&C). Information from the sensors is passed to a Regional Correlation Centre (RCC) which collates this information, fuses it and forwards a Recognised Air Picture (RAP) to various nodes in the C3I system.

The recipients of the RAP are the Sector Air Defence Operations Centre (SADOC), the Tactical Air Operations Centre (TAOC) and the Control Element (CE). The commander in the SADOC monitors the RAP, is responsible for all air defence operations within the sector and contributes to the situation awareness of higher command (the National Air Defence Operations Centre (NADOC)). The TAOC also monitors the RAP and is responsible for setting and maintaining the posture of its air defence assets which in this case are (blue) intercept aircraft. This is maintained through directives to the fighter aircraft squadron (SQN) and assigning control of intercept aircraft to the CE.

The CE is responsible for directing assigned intercept aircraft to hostile (red) aircraft tracks. This is achieved by monitoring aspects of the RAP and directing the fighters accordingly.

5.2 C3I system and scenario

Consider the C3I system for study to consist of the RCC, NADOC, SADOC, TAOC, CE and SQN as shown in Figure 5. That is, excluding the capabilities of the air defence assets such as the sensors and the intercept aircraft. The key features that might be inspected in this system are timeliness and quality of information and decision making.

In order to conduct such an inspection using the DICE simulation, a scenario that exercises the C3I system needs to be defined. That is, a scenario that both stimulates the system and is also influenced by that system. In this case, the scenario can be considered to be where red aircraft are conducting reconnaissance missions. The surveillance assets of the blue force have some capability to detect the red activity and convey this to the C3I system. Within the C3I system decisions need to be made regarding the nature of the activity which will eventually lead to the scrambling and directing of blue intercept aircraft.

The following sections will outline how such a system and scenario might be represented within the DICE simulation in order to permit an assessment of the surveillance, dissemination, assessment and response process discussed above.

5.3 Representing the C3I system

The C3I system to be studied is typically represented within the simulation through the use of artificial agents, human players and communication link delays. There are numerous optional configurations that can be established ranging from full automation using one or many artificial agents to the inclusion of one or more human players.

5.3.1 Human player allocation

It may be more appropriate to utilise a human player to represent a node of the C3I system than an artificial agent. This may be owing to a lack of data that permits an adequately realistic artificial representation or it may be desirable from a training or knowledge elicitation point-of-view.

Consider the case where the TAOC node were represented by a human player, as shown in Figure 6. The ADFORM facilities reported in reference 15 would currently be used to permit the receipt, creation and submission of messages by the player. In addition, the player might be presented with some CSS to assist his decision-making process. The concept of a CSS is exemplified in later sections with the use of a second copy of the ADSIM peripheral unit. In the longer term, alternative messaging and CSS might be employed.

The TAOC player would receive formatted textual messages from the RCC that convey the RAP as well as directives and approvals from the SADOC. The TAOC player would monitor the air picture and make decisions regarding the formation and maintenance of aircraft alert states and Combat Air Patrols (CAP). Definition and maintenance of such posture of the air defence assets would be achieved through communication via formatted textual messages to the SQN node. Decisions to scramble intercept aircraft to meet hostile tracks might require approval from the SADOC commander which would be addressed through identical communication means.

5.3.2 Artificial agent allocation

The remainder of the C3I network nodes would be represented through the use of artificial agents (see Figure 7) which, to date, would primarily consist of PN simulations. Rules that define the behaviour of each node would be represented within the PN. In the case of the CE, for example, rules would be implemented that reflect how that node responds to tasking from the TAOC; how it communicates with intercept aircraft; and what information is conveyed. Associated with all such rules is time information; namely, how long does it take to conduct a particular action. Such timings can be of fixed or variable duration.

Each PN node would have an associated tassel file that indicates what information will be provided by a node to others. For example, the RCC is

capable of providing a RAP message and, in this case, this tassel will be tied to the SADOC, TAOC and CE who are the intended recipients of this information; other nodes will not receive that type of message. Each net also has associated input mapping information which indicates what ADFORM that agent is able to accept and how it is translated into the internal database of that agent. Similarly, there is output mapping information also.

5.3.3 Communications

Communications delays can be represented by a number of means. For example, consider the time delay associated with the transfer of the RAP between the RCC and the SADOC. If these nodes were implemented as one node in the DICE simulation then the time delay, or the communication protocol that results in that delay, would be incorporated within that node also. If the RCC and the SADOC were implemented as separate artificial agents then the communications delay between the two can be represented by one of two means. Entries could be put in the Ingres database that specify either a fixed or statistically distributed time delay between the two nodes. Alternatively, PN could be used to provide detailed communications models for links. In the latter configuration, the communications delay between the RCC and the link agent would be zero, the actual delay would be computed within the link agent, and a zero delay would apply between that agent and the SADOC.

5.4 Representing the air defence assets

In the example application of Figures 4 to 9 there is a need to represent sensor capabilities and aircraft movement. Given the current repertoire of tactical models, this requirement could be addressed through the use of one copy of the ADSIM model (ADSIM1, as shown in Figure 8). In this role, ADSIM1 represents *ground-truth* information in that it generates the true air picture. The graphical display capabilities of ADSIM1 would be useful to the simulation controller in monitoring the course of the simulation.

The two-way interface ADSIM PUI would be employed with ADSIM1. Detection information from the surveillance assets would be output from ADSIM1, converted into appropriate messages and sent to the RCC node. Aircraft that become airborne due to the actions of the TAOC would be conveyed to ADSIM1 from the SQN node by a textual message which gets converted into appropriate input directives for ADSIM1, resulting in the creation of a new aircraft and flight path. Similarly, intercept control directives from the CE would be relayed to ADSIM1 resulting in modifications to the existing flight paths of the blue intercept aircraft. The conversion between the internal database of ADSIM1 and the ADFORM-based textual messages is achieved through the use of mapping rules in a similar manner to that employed with the PN agents. Tassel tying also features for peripheral units.

5.5 Employing a CSS for the human player

Peripheral units may be employed as CSS by human players to assist their decision making. A second copy of ADSIM (ADSIM2) might be used in such a role in this example, as shown in Figure 9. In this case, ADSIM2 would be used to display the perceived air picture, ie the RAP as used by the TAOC node. This would be achieved by making use of the ADSIM PUI discussed earlier but in an input mode only. That is, the RAP messages received by the TAOC node would be fed to ADSIM2 such that any latency and inaccuracies injected by the surveillance and C3I system are reflected in the display presented to the human player. Hence the resultant display might differ significantly from the true picture of ADSIM1.

5.6 Defining the initial scenario

The scenario generation facilities of the DICE simulation result in a collection of independent stimuli that are scheduled at initialisation. Ideally, the artificial agents should be general rules of behaviour that get conveyed their initial states prior to runtime. For this example, stimuli would include messages that specify the initial number and state of aircraft on the ground and in the air to the SQN and TAOC as well as any information that conveys initial tasking to such entities as the CE.

The ADSIM PUI has been designed such that ADSIM can be slaved to DICE stimuli. This permits the specification at initialisation of aircraft flight paths and sensor status that are considered to apply at zero simulation time. A different set of stimuli would apply to ADSIM1 than to ADSIM2.

5.7 Analysis opportunities

Simulation of the above example involves emulation of information flow within the overall system, activation of the rules of the artificial agents and actions by the human player. With the inclusion of a human player, it is more appropriate for the simulation to execute in real-time.

The general design and data recording features of the DICE simulation provide a number of analysis opportunities as discussed in Section 4.4. The following are examples for the case shown in Figures 4 to 9.

- A series of stimuli-to-response observations could be made for individual nodes such as the TAOC, SQN or CE.

- The military objective in this example is to intercept red aircraft before significant reconnaissance has been achieved. The timeliness and quality of

the information flow and decision making within the C3I system will contribute to the extent to which this objective is satisfied. Post-simulation interrogation of the database or suitable measures computed during runtime could be used to make judgements about this contribution.

- ADSIM1 and ADSIM2 respectively display and hold data on the actual and perceived air pictures. In addition, the data that drives these models is captured in both the logged inter-node message traffic and the record of activities internal to the artificial agents. The capability to compare the two pictures therefore exists and is another means of judging the timeliness and quality of the system under study.

- Critical path and general parameter sensitivity techniques could be employed to inspect the sensitivity of outcomes to variations within the C3I system. For example, the effect of varying the RAP update rate between the RCC and the TAOC could be investigated. It may be necessary to replace the human player with an artificial agent in order to conduct such processes.

6. Future Research and Development

A follow-on task is being addressed which has the following main emphases:

- The provision of simulation technology to the Defence organisation;
- Further development or acquisition of tools for C3I analysis;
- Applications to Defence studies;
- Interfacing simulation with operational C3I systems; and
- General measure of merit and analysis R&D.

Development of the DICE simulation and other quantitative analysis tools will continue within this task. It is particularly important that future development be driven by the lessons learned from application of the simulation to Defence projects and studies. Some of the areas to be addressed are discussed below.

The current scenario generation capability is adequate but limited and will need enhancing through increased robustness and visualisation tools that facilitate and extend useability. This is particularly important in order to extend the user base of the simulation to include military personnel, for example. Enhancements might include the integration of some Order of Battle (ORBAT) tool for the specification, maintenance and interrogation of blue and red forces.

Map displays would be particularly powerful in the front end of the simulation, particularly in the specification of the initial position, state and intentions of entities involved in the simulation. Such displays could also be employed as useful run-time display facilities.

The field of artificial intelligence needs to be researched further in search of techniques for increasing the artificial agent abilities to deal with uncertain or incomplete information, explain their actions and acquire knowledge through learning and observation of human interaction[17]. Any new techniques will be judged against any opportunities to extend the current PN approach.

Optimisation expertise has been applied to the core DICE simulation database in order to improve performance. The findings of this activity, as well as the results of ongoing effort to continually improve performance, will be implemented as part of future development.

Full compliance with DIS protocols is important to the DICE simulation since it opens avenues for longer-term interoperability with remotely located peripheral units such as battle simulations and human player facilities. This will necessitate monitoring developments in this field and assessing the extent to which C3I information exchange can be satisfied by the protocols.

Part of the simulation implementation facility involves specification of how the multiple processes that typify the simulation should be distributed across available processors. A capability, based on predicting data latency and hence simulation performance, to automate the process of determining the best distribution is desired.

7. Conclusion

A general-purpose suite of tools for the modelling and simulation of C3I systems has been developed. The primary capability is that of the DICE simulation which has the following key features[16]:

- The ability to graphically define the network of nodes and links that form the central C3I system under examination.
- The ability to represent communication over network links through stochastic or deterministic time delays.
- The ability to specify a scenario under which the C3I network will be exercised.

- The ability to artificially represent and emulate over time the functionality (input, output and internal activities) of network nodes through the use of artificial agents. Such agents can currently consist of Petri net simulations and simple alternatives such as look-up tables.

- The ability to assign human players to represent the actions of network nodes. A standard language is needed for communication between human players and artificial agents; ADF and DICE-specific ADFORM messages are used. A variety of ADFORM-related software has been developed including a GUI facility permitting human players to receive, create and submit ADFORM messages.

- The ability to define appropriate MOM to be used in a particular study and to develop artificial agents for the computation of those measures during run time. The ability to specify mission requirements for each measure.

- Simulation controller facilities for run-time monitoring and control.

- A simulation kernel that allows interoperation of autonomous artificial agents, human player facilities, controller facilities and PUI for interfacing to battle simulations and CSS, for example. A single and multiple execution capability exists as well as flexible execution rate.

- A core relational database architecture.

- Post-simulation analysis facilities allowing inspection of single and multiple simulation execution data. Features include the inspection of information flows and general effectiveness analysis through comparison of MOM values against mission requirements.

- A PUI that allows interoperation of the DICE simulation with an in-house developed air defence simulation ADSIM[19].

- A partially-developed PUI that will lead to full compliance with DIS protocols. This capability has been demonstrated through interaction with other DSTO DIS-related systems.

Non-interactive simulation, consisting of a collection of Petri net and other artificial agents is achievable. This flexibility is important for Monte Carlo and parameter sensitivity analyses which necessitate multiple executions of the simulation.

ADSIM is the first of many models that need to be readily available for representation of the overall tactical environment in a scenario. Other models

were investigated but practicalities did not permit interfacing to them. DIS compliance for the DICE simulation will open up more options.

In addition to the DICE simulation a Petri net explanation and analysis capability and GUI environment for conveying the underlying characteristics of a Petri net agent to a military domain expert was developed[7,11].

Simulation is a burgeoning technology within the Defence community. In particular, in the area of C3I the interoperation of simulated and real systems is regarded as a key requirement for mission rehearsal and other forms of training that also facilitate subsequent analysis. Also, the ready availability of C3I models and simulations is critical to the ability to rapidly respond to general queries and formal Defence capability studies concerned with information acquisition and general C3I system performance and effectiveness issues.

This report details developments to date in the DICE simulation and associated tools which are considered readily available for use in Defence projects and studies. A number of activities are being addressed under a new task which include interfacing with operational CSS and support to capability studies. The lessons learned from applying the simulation will significantly influence further development.

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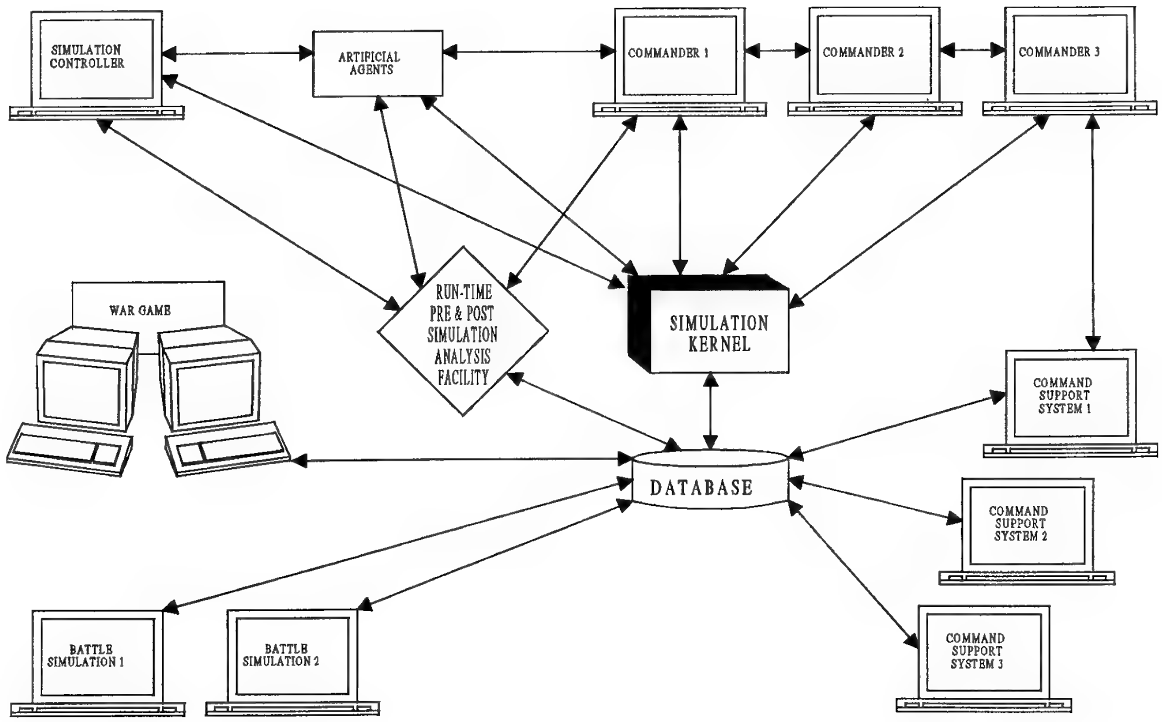

Figure 1 Functional diagram for DICE simulation environment

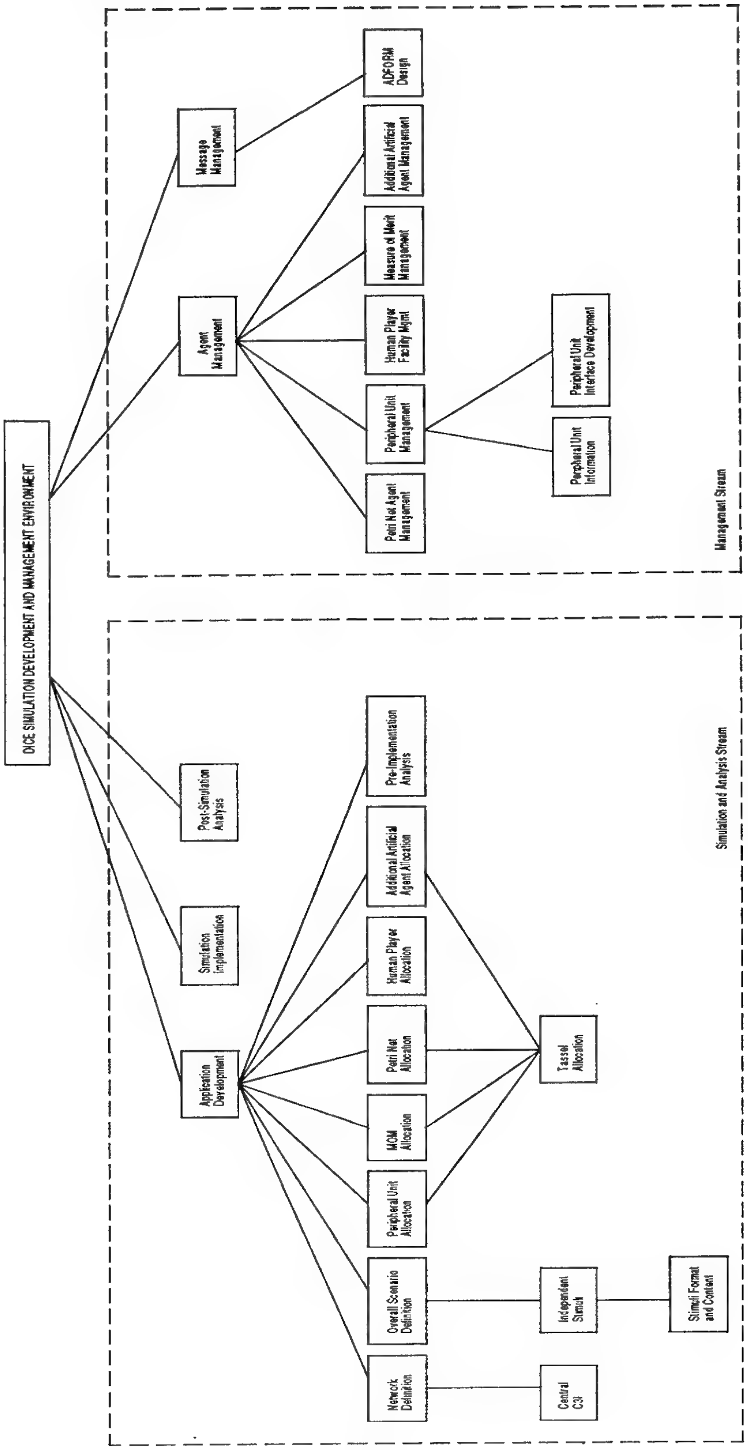

Figure 2 Structure of the DICE Simulation Development and Management Environment (DSDME)

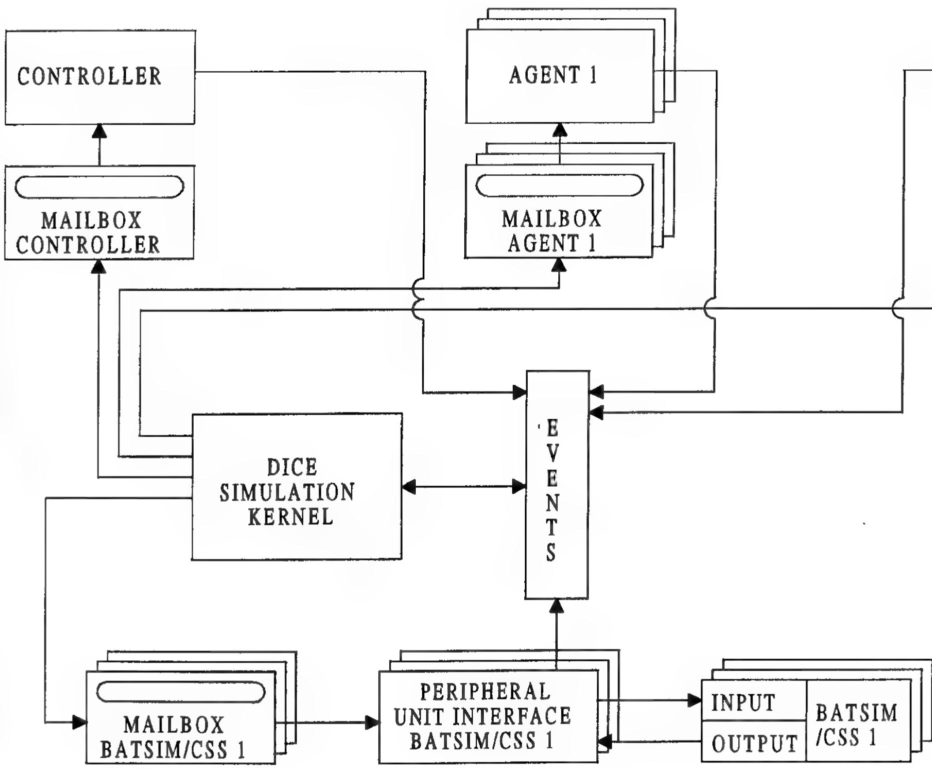

Figure 3   DICE simulation kernel and communication

KEY	
OTHR	Over-The-Horizon Radar
GBR	Ground-Based Radar
AEW&C	Airborne Early Warning and Control
NADOC	National Air Defence Operations Centre
SADOC	Sector Air Defence Operations Centre
TAOC	Tactical Air Operations Centre
RCC	Regional Correlation Centre
CE	Control Element
SQN	Squadron

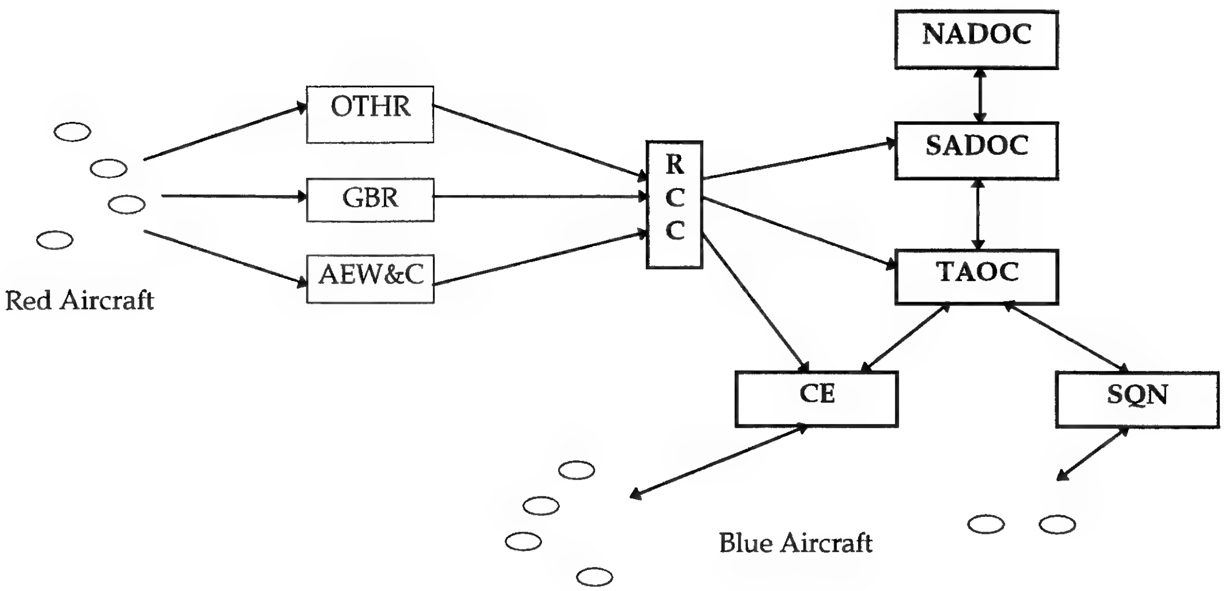

Figure 4 Air defence example application: overall system

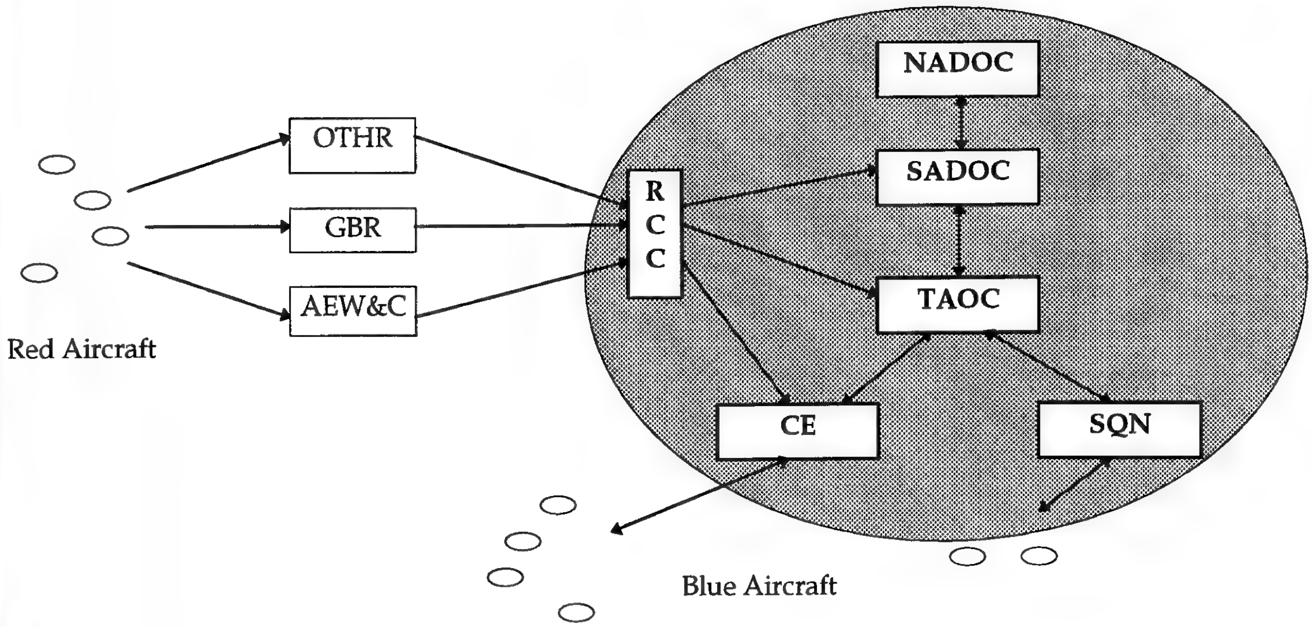

Figure 5 Air defence example application: C3I system

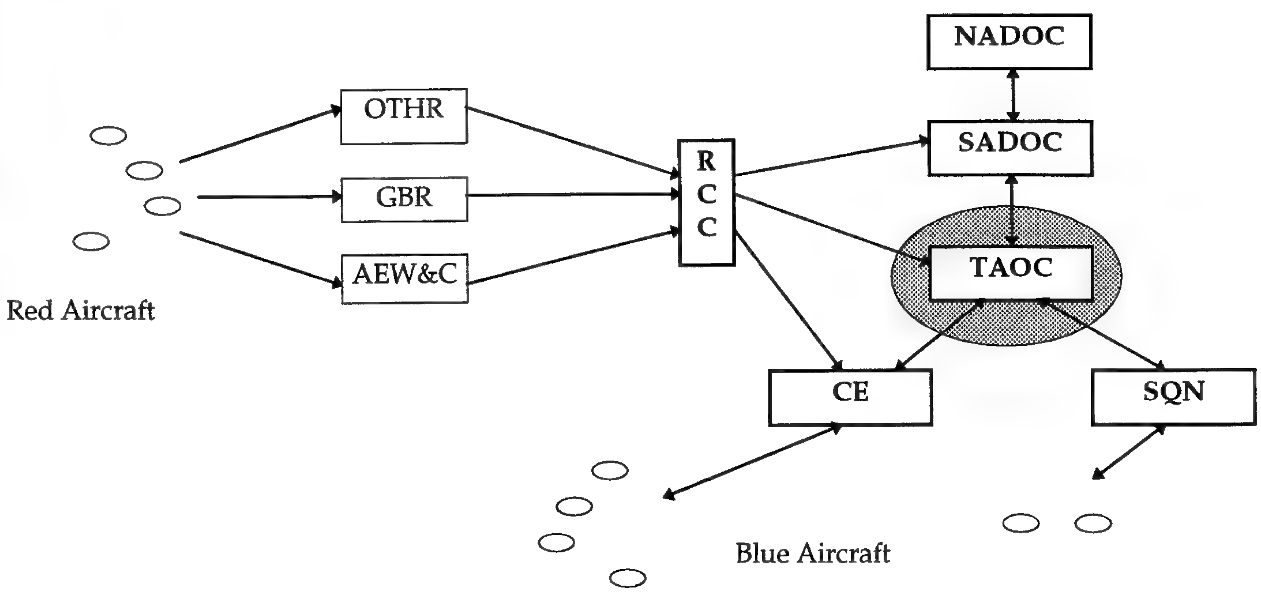

Figure 6 Air defence example application: human player allocation

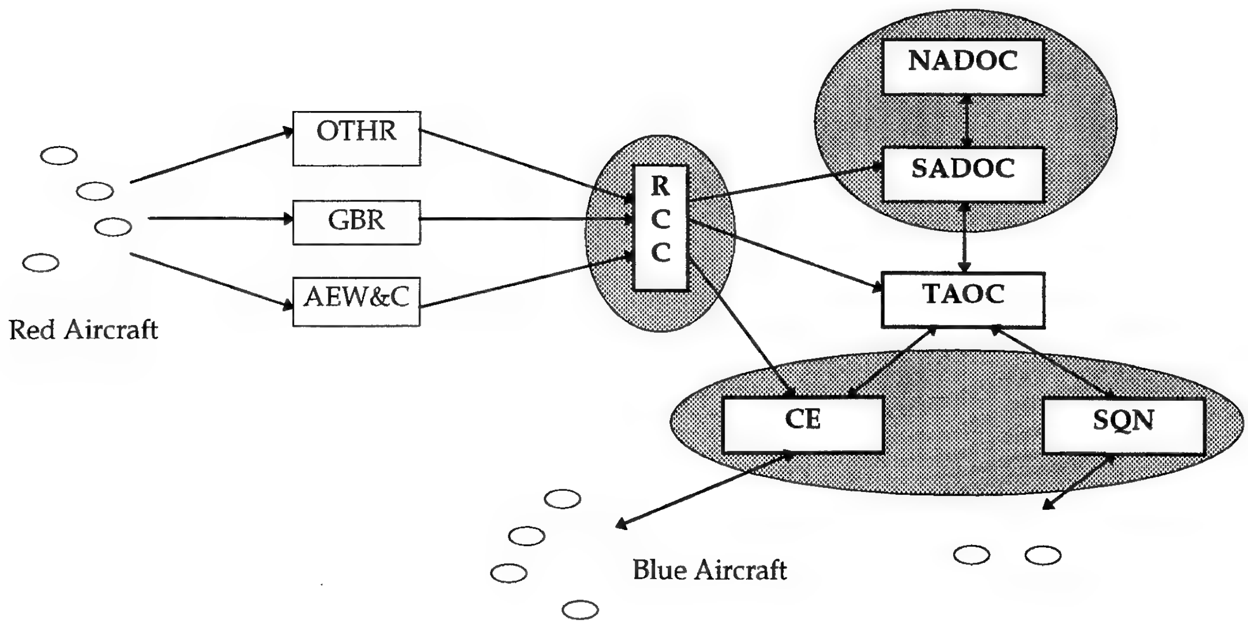

Figure 7 Air defence example application: Petri net agents

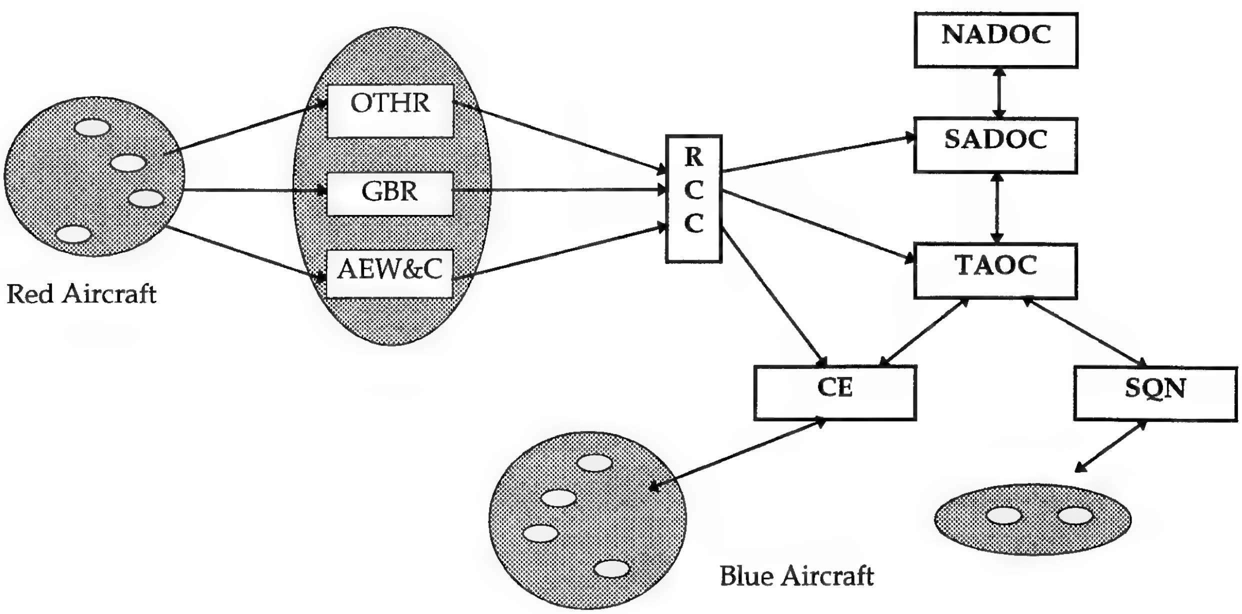

Figure 8 Air defence example application: peripheral units (ADSIM1)

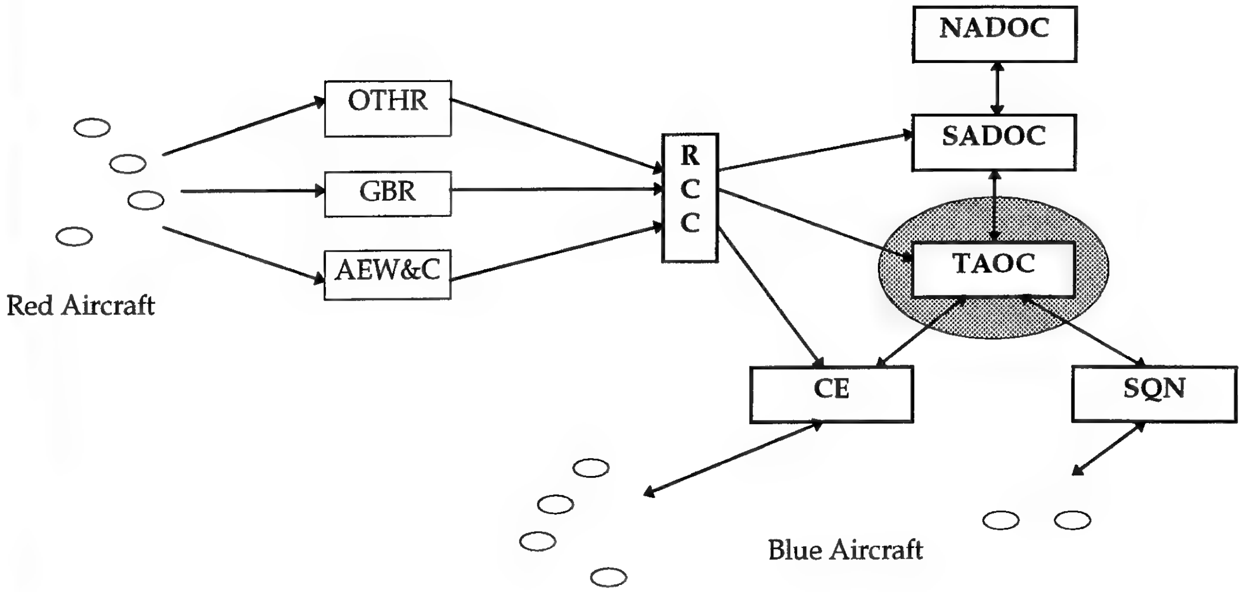

Figure 9 Air defence example application: peripheral units (ADSIM2)

The Distributed Interactive C3I Effectiveness (DICE) Simulation

Mike Davies, Carsten Gabrisch, John M. Dunn and Fred D.J. Bowden

(DSTO-TR-0485)

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19. ABSTRACT

Information Technology Division was tasked by the Headquarters Australian Defence Force to develop tools, through modelling and simulation, for effectiveness studies of Command, Control, Communication and Intelligence (C3I) systems. Such tools needed to allow for the study of systems at the strategic, operational and tactical levels, including all services and joint forces. The primary tool developed is the Distributed Interactive C3I Effectiveness (DICE) simulation in which human players are complemented by artificial agents. The DICE simulation environment can be connected to lower level battlefield simulations and war games which are used to represent the overall military mission, operation or battle. The impact of C3I aspects on the overall mission can be used to gauge C3I system effectiveness. What is termed Phase 1 of development has been completed and is reported collectively through a number of detailed documents. This report gives a substantial overview of the simulation capability along with areas of future research and development.